Shallow Water Laser Bathymetry: Accomplishments and Applications

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Introduction

Airbome Laser Bathymetry (ALB) is a technique primarily aimed at augmenting nautical chart production and bathymetric mapping capability in relatively shallow coastal waters. The potential of water-penetrating airborne laser radar to provide cost effective characterization of underwater topography to depths as great as 50 meters, depending on water clarity, has triggered a number of research and development efforts worldwide over the past three decades. Currently ongoing and aimed at providing operational ALB tools, are the Optech Incorporated "SHOALS" program for the U.S. Army Corps of Engineers, the Saab Instruments/Optech Inc. "Hawk Eye" program for both the Swedish Navy and the Swedish Hydrographic Department, and the Royal Australian Navy's "LADS" program.

The motivation to develop ALB technique to operational status is primarily two-fold: the speeding up of the surveying tasks that exist under the current mandate of the various hydrographic agencies, and the anticipated, significant savings in the cost-per-unit-area-surveyed. Millions of square kilometers of uncharted waters with depths of less than 50 m, that still exist worldwide, present a backlog of hundreds of ship-years to conventional acoustic surveying. Additionally, much of surveyed navigation routes have bottom types that are sufficiently dynamic, in the short term, to require frequent re-surveying. The much greater speeds, than those of surface vessels, of ALB platforms have already demonstrated that the needed surveys can be done more quickly and more economically. Furthermore, because it is airborne, the use of ALB to carry out surveys suited to its capabilities provides a benefit of flexible deployment in distant areas with small operational windows, or shallow areas unsuited to conventional surveying techniques. ALB also offers, as standard, the benefit of virtually uniform x-y sounding distribution.

Airborne Laser Bathymetry Technique

Airborne laser bathymetry is now a well proven technique for bathymetric surveying applications. Airborne laser bathymeters utilize the lidar (LIght Detection And Ranging) technique to infer water depth from the differential time-of-flight of an optical pulse transmitted from the aircraft to the water bottom through the air-water interface.

Laser-generated optical pulses, of wavelength suitable for propagation through water, are transmitted from an aircraft towards the water surface. An optical receiver, co-located with the transmitter, detects the pulse reflections from both the water surface and the sea bottom. The water depth is determined from the elapsed time between these two reflection/scattering events and the known speed of light in water, after accounting for the operating geometry and corrections for propagation-induced biases and waveheight and tide effects.

In the typical operational scenario, successive laser pulses are scanned sequentially across the water surface to produce, when combined with the aircraft's forward velocity, a swath of soundings of near-uniform spatial distribution. The horizontal coordinates of each of the soundings are determined from the knowledge of the aircraft position, altitude and attitude, the laser beam propagation direction with respect to the aircraft, and the measured water depth.

In general, ALB systems consist of four major subsystems: the lidar transceiver, the positioning subsystem, the data acquisition/control/display subsystem, and the ground-based data processing subsystem. The lidar transceiver is responsible for transmitting and directing the laser pulses onto the water surface, for detecting/measuring the optical pulses returning from the surface/bottom, and for determining their absolute time-of-flight. The positioning subsystem is used to determine, with great accuracy, the absolute position and attitude of the aircraft throughout the survey mission in order to allow accurate determination of the soundings' position.

The data acquisition/control/display subsystem controls and coordinates information from all other components of the airborne systems, records all relevant data and system information onto a removable medium for later processing, and provides man-machine interfaces between the airborne system, its operator and the aircraft pilot. The ground-based processing subsystem is used for off-line processing of ALB data, including the transformation of raw ALB sounding information through to a fully-verified XYZ digital database of soundings suitable for further analysis and interpretation by the end-user (hydrographer or other).

Historical Overview of ALB Programs

In the late 1960s, soon after the first laser demonstrations, the U.S. Navy sponsored certain classified efforts associated with submarine detection using airborne laser-based systems. Following these beginnings[1], experimental profiling systems were developed in the United States by the National Aeronautics and Space Administration (NASA) and the U.S. Navy, by the Canada Centre for Remote Sensing (CCRS)/Optech in Canada, by the Royal Australia Navy (RAN), and by the Defense Research Establishment (FOA)/Optech in Sweden.

Second-generation, primarily experimental and scanning, systems were developed in the late 1970s and early 1980s: the Airborne Oceanographic Lidar (AOL), a joint U.S. effort from NASA, the National Oceanographic and Atmospheric Administration (NOAA), the U.S. Navy and AVCO; the Weapons Research Establishment Laser Airborne Depth Sounder II (WRELADS II) in Australia; and the Hydrographic Airborne Laser Sounder (HALS), from the Defense Mapping Agency (DMA), NASA, the U.S. Navy and AVCO. An experimental system was also developed and tested in the Soviet Union.

The mid- to late-1980s saw the development of operational prototypes as a major thrust: LARSEN-500 from the Canadian Hydrographic Service (CHS)/CCRS/Optech; FLASH-1 from FOA/Optech; and the Airborne Bathymetric System (ABS) from the U.S. Navy, which incorporated the earlier Hydrographic Airborne Laser Sounder (HALS) and other technology.

In the 1990s, truly operational systems were developed: the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) system from the U.S. Army Corps of Engineers (USACE)/Optech; Hawk Eye, a SHOALS derivative, built by Saab Instruments/Optech for the Swedish Navy and Hydrographic Department (2 systems); and the Australian Laser Airborne Depth Sounder (LADS) from RAN/BHP Industries.

Other systems developed and tested during the 1980s and 1990s include the Blue-Green Oceanographic Lidar (BLOL) from China, three multi-purpose research systems from the USSR, a prototype profiling system from Thomson-Sintra-ASM of France, and the classified Oceanographic Water Lidar (OWL) system in the U.S. The most recent is the Australian LADS Mk. II system, currently under development. There have also been prototype systems developed specifically to detect underwater mines, such as the Airborne Laser Radar Mine Sensor (ALARMS) built by Optech for the U.S. Defense Advanced Research Projects Agency (DARPA).

In nearly three decades of ALB development, there has been considerable advancement of the required technology, both in terms of the associated components and of the measurement technique itself. It is interesting to understand some of the driving forces that resulted in the development of the various generations of systems and how the later efforts were indisputably linked to those previous.

For example, the LARSEN-500, as one of the first operational prototypes flown, was undertaken based on the unique charting requirements[2] imposed by operation in the icepack-prone arctic regions: the need for rapid deployment, swiftness of survey and flexibility of plan. The Swedish FLASH-1 system, essentially an evolution of the LARSEN-500 transceiver with a new Saab programmable scanner incorporated, was primarily developed to augment the capabilities of the anti-submarine defence force. In a similar way, the U.S. DARPA-sponsored ALARMS system, a purpose-built airborne lidar for water-borne mine detection based upon an earlier proven ALB receiver configuration, was developed from urgent requirements related to the Persian Gulf War.

The Australian ALB development effort, including the WRELADS and LADS variants, grew out of the unique hydrographic requirements imposed by the vast, rugged and largely isolated Australian coastline. The SHOALS (discussed in more detail below) and both Hawk Eye systems, although based largely upon a similar system backbone, were all developed as next-generation operational systems each with their own peculiarities, reflecting their individual requirements.

SHOALS System Development and Capabilities

Early in the 1980s the U.S. Army Corps of Engineers, recognizing the need to augment their existing hydrographic survey capabilities, began evaluations of alternative technologies which would allow them to perform surveys quickly and accurately, and in a fashion at least as cost-effective as with traditional methods. In 1988 the USACE and the Canadian government began a cooperative program[3] to develop and field prove a next-generation ALB system to fulfill their operational requirements for "reconnaissance" and "condition" type surveys on a variety of navigational channels throughout the continental U.S.

For maximum deployment flexibility, SHOALS was originally installed in a Bell 212 helicopter platform, and is partly housed in an external pod (lidar transceiver and attitude subsystems) and partly inside the aircraft (data acquisition/control/display, positioning, and pilot guidance subsystems). It requires a single operator for survey performance.

Differential GPS (DGPS) is used to provide positioning information to the aircraft in realtime. A pilot reference function assists the accurate navigation of the helicopter along pre-selected flight tracks. Additionally, kinematic GPS (KGPS) with on-the-fly (OTF) ambiguity resolution has recently been implemented, which eliminates the necessity for collecting tidal data concurrent with the lidar data.

A Litton LTN-90 inertial reference system (IRS) is used to indicate the aircraft altitude and attitude for accurate realtime and post-processed soundings' positioning, and is also used to provide dynamic correction to the scanner pointing direction (see below).

The lidar transceiver consists of a 200 Hz frequency-doubled Nd:YAG laser which produces both green (532 nm, 3-5 mJ, 5-6 nsec) and infrared (1064 nm, > 5 mJ, 7-9 nsec) pulses. A two-axis, pitch/roll-corrected scanner is used to sweep the laser beam pointing direction across the aircraft track in order to produce a nearly-uniform distribution of laser spots on the water surface.

An optical receiver collects the light returning from the surface/volume/bottom of the water, and optical signals are measured at the green (2 channels) and infrared wavelengths and also near 650 nm (red wavelength, corresponding to the Raman-scattered light from molecular water, excited by the green laser light). Two green channels are used so that optimized detection for shoal and deeper bottoms can be accomplished simultaneously.

The signals from each of the channels are pre-processed using a sophisticated analog processing module and are digitized (for each laser sounding) and recorded for use in off-line processing. All other required system parameters, as well as the scanner angles and the aircraft position and attitude, are also recorded for later processing. A down-look video system simultaneously records the area being surveyed below the aircraft.

All of the data acquisition, control and display functions are performed by a dedicated, VME-based airborne computer. This computer handles all survey aspects such as flightline management (referenced to a pre-defined survey plan), pilot referencing, video annotation, data collection and recording, system integrity verification, operator interaction, and the realtime calculation of sounding positions and approximate depths.

The ground-based processing system is used to transform the raw recorded data from the SHOALS airborne system to XYZ output data suitable for subsequent geographic manipulations, analysis and interpretation. This process involves both automatic processing and manual editing steps (if needed), and allows for various ancillary data input such as tidal information.

Compared to previously developed ALB systems, SHOALS incorporates several key improvements which increase its utility for surveying applications. The programmable, two-axis, gyro-stabilized scanner represents a tangible benefit for the efficient production of uniform sounding distribution. The roll and pitch compensation allows very straight swaths of laser soundings to be generated, which aids the elimination of "holidays" in the data collection process.

The use of multiple channels[4] (green, IR and Raman) for measuring the water surface location for each laser shot increases the probability that the surface can be accurately located over as wide a range of operational conditions as possible, and allows a measure of internal consistency verification unavailable otherwise. This is important since the depth measurement is ultimately limited by the ability to properly locate the instantaneous sea surface. Similarly, the use of separate shallow- and deep-optimized bottom channels facilitates the compression and subsequent capture of the tremendous signal dynamic range which is encountered both over the expected system operational range, and also within the relevant temporal duration of each signal for a single sounding.

Since SHOALS determines the instantaneous surface location across the entire area of the swath, and incorporates the measurement of aircraft vertical acceleration, it is possible to find the mean water level at the time of surveying and to reference all water depths to this datum. This technique[5] permits the effects of instantaneous waveheight and long-period swell to be removed from the measured depths.

The incorporation of such a waveheight analyzer in the groundbase processor also provides SHOALS the capability for surveying inland from the normal off-shore surveys (DGPS mode). In this way, land elevations may also be measured albeit with some restrictions on the proximity to surveyed water areas. However, with the utilization of the aforementioned KGPS/OTF mode of positioning, these restrictions are removed, and SHOALS can survey land topography independently.

The groundbase processor has been developed around a relational database, allowing maximal flexibility for investigating system performance and data characterization. Refinements in the structure for the processor have also allowed an increase in the processing ratio (of data processing time to survey time) from an original value greater than 5:1 to approximately 1:1. Current development is aiming to speed the processing still further in order to accommodate a doubling of the data acquisition rate without increasing the actual processing time.

The main limitations of SHOALS for depth determination are related to its maximum depth capability, weather-related phenomena, and bottom structure. Water clarity, in particular, limits the ability of the laser light to penetrate to the bottom, thereby resulting in a clarity-dependent maximum depth capability as shown in Table 1. The minimum depth capability for SHOALS is currently not a concern; using a special "shoreline depths" mode of processing, the system is frequently capable of continuous topographic mapping from submerged bottoms onto shore. High surface waves, heavy fog and precipitation, and sun glint conditions act to decrease the depth penetration and/or measurement accuracy. Similarly, heavy bottom vegetation and "fluid mud" act to limit the system performance.

The SHOALS system performance for typical surveying applications is given as in Table 1.

Table 1: Nominal SHOALS System Performance

Parameter	Value	Notes
Measurement Rate	200 soundings/sec	
Altitude for data collection	200 – 400 m	
Sounding Density	4 x 4 m 6 x 6 m 8 x 8m	200 m altitude, 50 knots 300 m altitude, 70 knots 400 m altitude, 85 knots
Area Coverage	3 nm^2/hr > 6 nm^2/hr > 10 nm^2/hr	200 m altitude, 50 knots 300 m altitude, 70 knots 400 m altitude, 85 knots
Maximum Depth Capability $(Kd)_{max}$	> 3.0 (day) > 4.0 (night)	K = diffuse atten. coeff. (1/m) d = bottom depth (m)
Maximum Depth Range	40 m	
Minimum Depth Capability	0 – 1 m	see below
Horizontal Accuracy	± 4 m (DGPS) ± 1.5 m (KGPS)	1 standard deviation
Vertical Accuracy	± 20 cm	1 standard deviation
Data Processing Ratio	1 : 1	

In Table 1 for both the sounding density and area coverage parameters, the given values are a function of the aircraft altitude (m) and the aircraft speed (knots). The minimum depth capability is shown to be in the range 0 to 1 meters; in the normal mode of operation SHOALS has a minimum depth capability of about 1 m, whereas the "shoreline depth" mode of operation frequently allows continuous measurement from subsurface bottoms to on-shore elevations. The vertical accuracy listed in Table 1 has been demonstrated to depths at least as great as 30 m.

SHOALS Results and Achievements

In this paper we wish to focus on the results and achievements of, specifically, the SHOALS system towards shallow-water bathymetry, due to the multiplicity of applications for which the system has been utilized.

The SHOALS system successfully completed extensive field trials[6] in March 1994. Immediately following this verification procedure, SHOALS proceeded to survey two areas of central Florida Bay (~ 13 km^2) to demonstrate its capability for resolving some complex subsurface topography which was inaccessible using conventional survey technology.

SHOALS has conducted numerous one-time, and some repeat, surveys in 17 states and the Yucatan Peninsula of Mexico, in the nearly four years since its field verification was completed[7,8]. Approximately 220 survey projects have been performed, resulting in a total areal coverage greater than 2,750 km^2. The individual projects were performed to address specific objectives, including nautical charting and navigational hazard identification, hurricane and coral-reef damage assessment, beach nourishment monitoring and design, sea-grass delineation, erosion monitoring (storm response), navigation channel inspections, military applications and others. We wish to highlight several of the projects in order to indicate the capabilities of ALB, and in particular SHOALS, for shallow-water applications.

Yucatan Peninsula, Mexico

SHOALS first international mission was conducted over a 3-month period early in 1996, off the Yucatan Peninsula near Cancun, Mexico. The survey was performed for the U.S. Naval Oceanographic Office and the Mexican Navy Director of Oceanography. The objectives were to familiarize the U.S. Navy with ALB technology prior to their intended procurement of such a system, and to perform for the Mexican Navy an extended nautical charting operation in an area of high priority.

During the project approximately 800 km^2 area was surveyed, comprised of 133 survey missions and more than 100 million individual soundings. The sheer volume of data collected (approximately 12 Gbyte/day airborne lidar raw data) presented its own challenges for data processing, verification and management.

Although one of the primary strengths of SHOALS is its capability for fast turnaround time on survey projects (quick deployment, surveying and final data production), this particular project demonstrated its ability to provide large-area coverage: to collect, process and integrate large volumes of high-resolution data seamlessly over a relatively extended time period.

New Pass, Florida

New Pass is one of three exchanges between Sarasota Bay and the Gulf of Mexico, located between Longboat Key and Lido Key on the west coast of Florida. The pass is of particular importance to USACE since they are responsible for maintaining a navigable channel within it.

New Pass was the first navigation project surveyed by SHOALS, and also the project re-surveyed the most times. Since SHOALS became operational in 1994, this area has been surveyed a total of five times and represents a total surveyed area greater than 30 km^2 with over 3 million soundings, which was surveyed in less than 12 hours. This detailed, full-coverage monitoring over a 32-month period has allowed coastal engineers the opportunity to construct a precise, three-dimensional modeling of the pass and to infer an accurate, quantitative assessment of the sediment transport through the area[9].

The high-resolution SHOALS data acquired during this period not only enabled the sediment budget determination, but was also notable for additional reasons: it provided a high-resolution depiction of a large area which had recently been mined for a neighboring beach restoration project, it highlighted the capability for the system to acquire large amounts of data in shallow areas (much of the area having depths less than 2 m) where conventional survey technologies would be limited, and it also provided a quantitative evaluation of the southward-migrating trend of the navigation channel.

East Pass and Panama City Beach, Florida

In October 1995, subsequent to the passage of Hurricane *Opal* across the Florida panhandle, USACE was tasked to quickly and accurately assess post-storm conditions. This was done in the two critical areas of East Pass and Panama City Beach. The intensity of the storm had caused extensive dune and property damage throughout the panhandle, and it was apparent that there would be significant, concurrent bathymetric changes in the area requiring urgent assessment.

Some 10 days after the storm passage, SHOALS performed a 2.6 km^2 area of East Pass, comprised of about 0.3 million soundings, in less than an hour. On the same day as the survey was flown, data processing to hard-copy output was completed, as were quantitative estimates of the required navigational passage dredging and initial estimates of accompanying jetty and other damages. During the same emergency response project SHOALS also surveyed an 18 km^2 survey of Panama City Beach, comprised of over 1 million soundings, within a 3 hour period.

This project[10] indicates the ability of SHOALS to provide rapid, but accurate, emergency damage response. In East Pass and Panama City Beach the highly developed nature of the areas required fast determination of storm-related impacts so that reparation could begin as soon as possible.

Ft. Pierce, Florida

The SHOALS survey of Fort Pierce, in the spring of 1997, represented the first project completed using the KGPS/OTF mode of positioning. Although this area represents another tidal inlet, and is therefore most important to the USACE for reasons related to monitoring and maintenance of its near-shore navigational channel, the high-resolution data acquired also allowed excellent coverage of the upland beach and dune system.

Figure 1 illustrates a profile map of the inlet and beaches area derived from the SHOALS data. The two jetties are seen near the middle of the figure, extending off-shore in an east-north-easterly direction, along with the navigation channel between them. The beach/dune system is seen as the narrow, dark feature near the bottom third of the figure, aligned essentially perpendicular to the jetties.

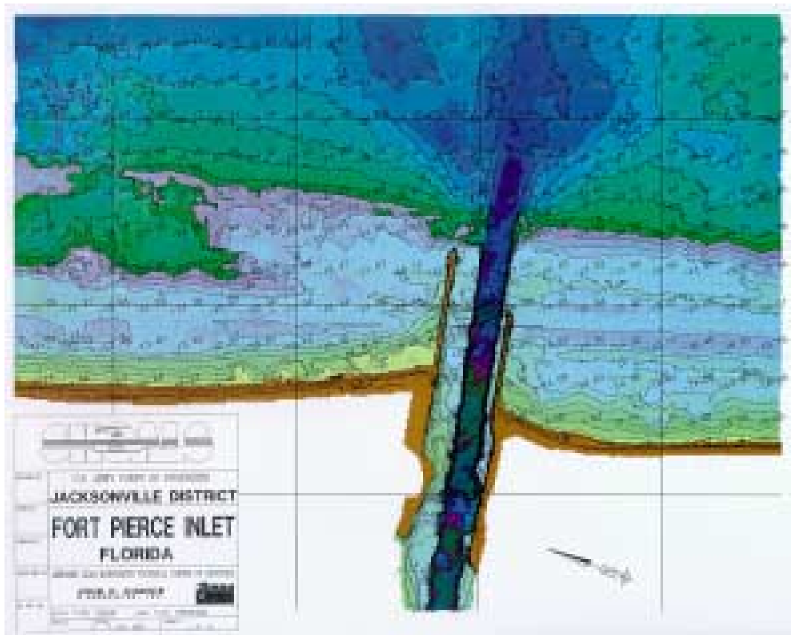

Figure 1 Fort Pierce Inlet, Florida

As discussed earlier, the KGPS/OTF mode of positioning allows SHOALS to survey onshore with virtually complete autonomy from water bodies. The aforementioned beach/dune areas are sufficiently removed from the adjoining inlet that operation in the DGPS mode would not have provided anywhere near the areal coverage achieved. The tremendous utility of this tool, with a capability to survey both on- and off-shore within the same flight mission, will no doubt only become apparent as more KGPS/OTF surveys are conducted in future applications.

Future Development

The capabilities demonstrated by SHOALS indicate to what a large extent the current generation of operational ALB systems are useful for numerous coastal, and onshore, surveying applications. The SHOALS development effort essentially began with a requirement for accurate and timely coastal hydrographic surveying. Over the course of the SHOALS system development, there has been a symbiotic evolution of the system capabilities and the applications for which it has been utilized.

We expect this trend to continue as the ALB technology improves. It is important to remember that certain of the key components that allow SHOALS to function were, at the time of its design and construction, custom development items. With the rapid technological progress occurring, in particular with laser sources and computer hardware/software, some of these items are much closer to being available COTS (commercial, off-the-shelf). This technological advancement for the key components has positive implications for future ALB systems in terms of increased performance and reliability, and reduced cost.

The SHOALS system is currently undergoing an extensive upgrade process which will double the system data acquisition rate to 400 soundings/sec, thereby allowing several advantages in overall system performance. The higher data acquisition rate allows the aircraft to fly higher and faster, with a corresponding increase in swath width and overall area coverage rate, while maintaining the sounding density. The increased coverage rate will reduce the surveying cost per square kilometer.

Two positive by-products of the upgrade are the required switch to diode-pumped laser technology, which will yield greater reliability of the laser source in extended field use, and less power consumption. As discussed earlier, continuous advances in the groundbase processor are also being made, to decrease the processing time and make the processing algorithms more robust over a large range of environmental and operational conditions.

A final positive benefit of the SHOALS upgrade is the capability for the system to be flown on a fixed-wing, rather than a helicopter, platform. The original SHOALS system was installed in a helicopter, in order to provide a high sounding density. The increased datarate resulting from the system upgrade will allow adequate sounding density at the higher speeds of fixed-wing aircraft. This has the potential for further reducing the cost of surveying per unit area, since the operating costs for suitable fixed-wing aircraft are lower than those for helicopters such as the Bell 212 used for SHOALS.

In addition to this work, we are pursuing considerable on-going research to investigate the potential for development of both shipborne (mast-mounted) lidar for water-borne obstacle/hazard detection, and also for an ALB system designed to operate on an unmanned airborne vehicle (UAV). We feel that the potential applications for such systems are numerous, and the operational and logistical advantages are great, but as always the ALB end-user community must drive the requirements.

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